T-REX: BARE ELECTRO-DYNAMIC TAPE-TETHER TECHNOLOGY EXPERIMENT ON SOUNDING ROCKET S520

Takeo WATANABE[1], Hironori A. FUJII[2,3], Tairo KUSAGAYA[4]
Hironori SAHARA[4], Hirohisa KOJIMA[4], Shoichiro TAKEHARA[5]
Yoshiki YAMAGIWA[6], Susumu SASAKI[7], Takumi ABE[7]
Koji TANAKA[7], Khoichiro OYAMA[7], Takuji EBINUMA[8]
Les JOHNSON[9], George V. KHAZANOV[10]
Juan R. SANMARTIN[11], Mario CHARRO[11]
Michiel KRUIJFF[12], Erik J. van der HEIDE[13], Binyamin RUBIN[14]
Francisco J. Garcia de QUIROS[15]
Pavel M. TRIVAILO[16] and Paul WILLIAMS[16]

[1] Teikyo University, 1-1, Toyosatodai, Utsunomiya, Tochigi 320-0003, JAPAN
TEL: +81-(0)42-585-8694, FAX: +81-(0)42-585-8694, E-mail: nabetake@ase.teikyo-u.ac.jp

[2] Kanagawa Institute of Technology, 1030 Simoogino, Atugi, Kanagawa 243-0929, Japan

[3] Nihon University, 7-24-1, Narashinodai, Funahashi, Chiba 274-8501, Japan

[4] Tokyo Metropolitan University, 6-6, Hino, Tokyo 191-0065, Japan

[5] Tokyo Metropolitan University, 1-1 Minami-Ohsawa, Hachioji, Tokyo 192-0397, Japan

[6] Shizuoka University, Shizuoka 432-8550, Japan

[7] Institute of Space and Astronautical Science, JAXA, Sagamihara, Kanagawa 252-5210, Japan

[8] University of Tokyo, Tokyo, Japan

[9] NASA George C. Marshall Space Flight Center, AL, 35812, U.S.A.

[10] NASA Goddard Space Flight Center, MD, 20771, U.S.A.

[11] Universidad Politecnica de Madrid, Madrid, 28040, Spain

[12] European Space Agency, 2201 AZ, Noordiwijk, The Netherlands

[13] Bradford Engineering B.V., 4600 AH, Bergen on Zoom, The Netherlands

[14] Colorado State University, Fort Collins, CO, 80523, U.S.A.

[15] Emxys, S/N 03202 Elche(Alicante), Spain

[16] RMIT University, Melbourne, Victoria 3083, Australia

Abstract

The project to verify the performance of space tether technology was successfully demonstrated by the launch of the sounding rocket S520 the 25th. The project is the space demonstration of science and engineering technologies of a bare tape electrodynamic tether (EDT) in the international campaign between Japan, USA, Europe and Australia. Method of "Inverse ORIGAMI (Tape tether folding)" was employed in order to deploy the bare tape EDT in a short period time of the suborbital flight. The deployment of tape tether was tested in a various experimental schemes on ground to show high reliability of tape tether deployment. The rocket was launched on the summer of 2010 and deployed a bare electro-dynamic tape tether with length 132.6 m, which is the world record of the length deployment of tape tether. The verification of tether technology has found a variety kind of science and technology results as the first in the humankind and will lead a large number of applications of space tether technologies.

1. Introduction

The space tether technology is indispensable in constructing and also maintaining large space structures, which are designed for future space development including a solar power satellite and deep space exploration. Tether technology has such many advantages as simple structure, compact package, very long lightweight structure, autonomous construction with little help of the astronauts, and also active electro-dynamic thruster. [Refs.1 & 2] It is thus necessary to verify tether technologies in space those performances expected as elements of space structures.

Electro dynamic tether (EDT) is one of the applications of tether technology to be verified in space. The EDT is a long conductive cable or tape made from an electricity conductive material such as aluminum. Electrons subtracted from ionosphere enters at one end and issues at the other end for the EDT orbiting the Earth. The Earth's magnetic field then generates electric voltage in the EDT [Ref.4]. The EDT can be employed as a generator to transfer orbital energy into electrical energy and also as a thruster to transfer electric energy into orbital energy. The present project is to verify the fundamental technology for such important tether applications. The other objective of the present proposal is the scientific study to incorporate the conductive tether by employing an Aluminum bare tape tether.

The bare tape EDT tether technology is able to generate thrust without use of any propellant and many applications include the elimination of space debris and re-boost of the international space station by generating the drag in interaction between electric current in tether and the Earth magnetic field. The demonstration will also be very effective to examine the possibility of the rotating electro-dynamic tether to Jupiter mission application to enable simple entry into the atmosphere of Jupiter, or lunch free tour to Saturn satellites [Ref.5]. It may be noted that de-orbiting of defunct satellites is indispensable for our future space missions to reduce the number of debris, and constitute one of the main and relevant commercial applications of the technology.

Space tether technology will extend the applicability in its utilities in accordance with the advance of space tether technology [Ref.6].

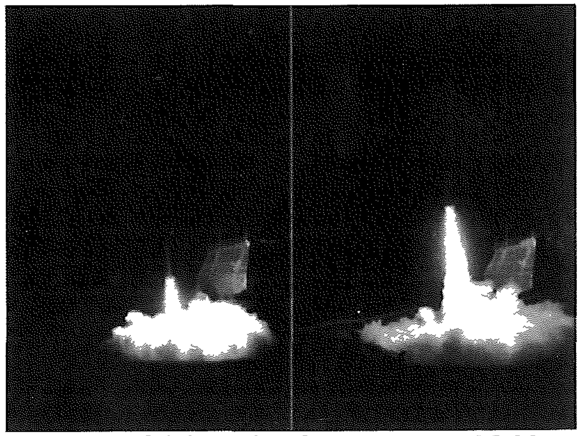

Fig.1 Successful launch of S520-25 at 05:00 on 31st August 2010 [Ref.3].

2. Verifications of Tether Technology in Space

A verification of tether technology was conducted for a bare tape EDT deployed from a sounding rocket, S520 [Refs.3 & 4]. The S520-25, 25^{th} of S520, was launched to an altitude of 307 km at 5:00am on 31st August of 2010 by ISAS/JAXA from Uchinoura site in Japan to southeast direction (Fig.1). The tape EDT was deployed to the flight direction in order to cross with the direction of the Earth magnetic field by almost 45 degrees, which was not controlled but was measured by a magnetometer. The objective of the projects was to verify experimentally the performances of a bare EDT by using tape tether in space from both scientific and engineering aspects including 1) swift and high reliability deployment of long tape tether, 2) fast ignition of a hollow cathode to provide electricity to electro-dynamic tether, 3) demonstration of EDT in collection of electrons, 4) verification of electron collection theories including OML (Orbit Motion Limit) theory, 5) atmospheric entry of tape tether, and 6) space tether robot motion control. Since these experiments were conducted simultaneously. This project was named Tether technologies Rocket Experiment, "T-Rex".

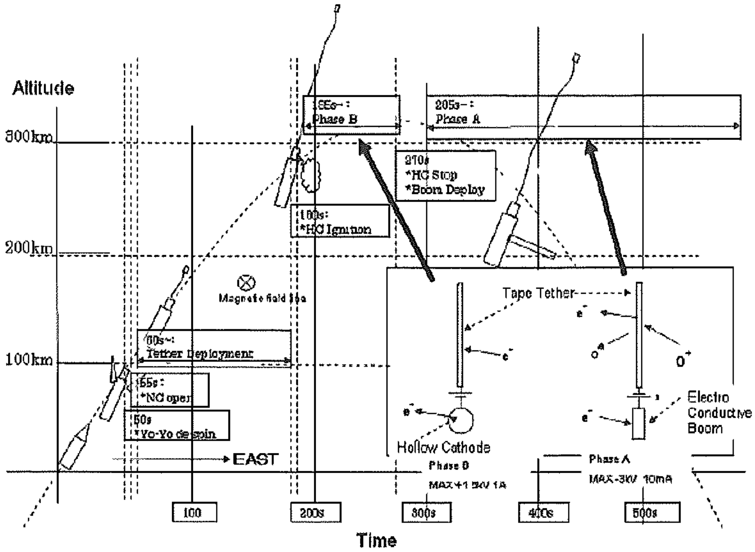

Fig.2 Experimental sequence of the sounding rocket experiment.

The tether was a bare EDT, which is a reinforced aluminum tape tether with width 25 mm and thickness 0.05 mm, and the science experiments employed the Langmuir probe as a main measurement device. Experimental sequence of the sounding rocket experiment is shown in Fig.2. The tether would be deployed in its length through 300 m in 120 seconds in order to afford sufficient time for science experiments for about 300 seconds in space.

The science experiment-phase A was a test of OML current collection in orbit. The OML theory constructed in the 1920s must be confirmed for the conditions of an orbiting tether in LEO. The test was expected to be carried out in the Pro-SEDS (Propulsive Small Expendable Deployer System)[Ref.7] project, which was canceled due to the possibility of hazardous collision with the International Space Station. The present experiment was thus be the first OML experiment in space [Ref.8].

The project T-Rex has successfully completed most of its technical objectives and the technologies demonstrated will play important roles in the course of future space development. Specifically, a conductive tether opens unique opportunities for science that are not limited to testing OML collection under orbital conditions and generating convenient electron beams. The project was an European/ American/ Australian/ Japanese International Campaign and the team of the project consists of (at the start of the project) Hironori A. Fujii, Takeo Watanabe, Hironori Sahara, Tairo Kusagaya, Hirohisa Kojima and Koh-Ichiro Oyama at Tokyo Metropolitan University, Japan, Susumu Sasaki, Kohji Tanaka, Takumi Abe, and Manabu Shimoyama at ISAS/JAXA, Japan, Yoshiki Yamagiwa, and Hirotaka Ohtsu at Shizuoka University, Japan, and Mengu Cho at Kyusyu Institute of Technology, Japan, Toru Hada at Kyusyu University, Japan, Juan R. Sanmartin, and Mario Charro at Unversidad Politecnica de Madrid, Spain, Alain Hilgers and Jean-Pierre Lebreton at ESA, Europe, Michiel Kruijff, Erick J. van der Heide, and Fabio De Pascale at Dealta-Utec.SRC, Netherlands, John Williams and Binyamin Rubin at Colorado State University, USA, Les Johnson at NASA/MSFC and George V. Khazanov at NASA/GSFC, USA, and Pavel M. Trivailo and Paul Williams at Royal Melbourne Institute of Technology, Australia[Ref.9].

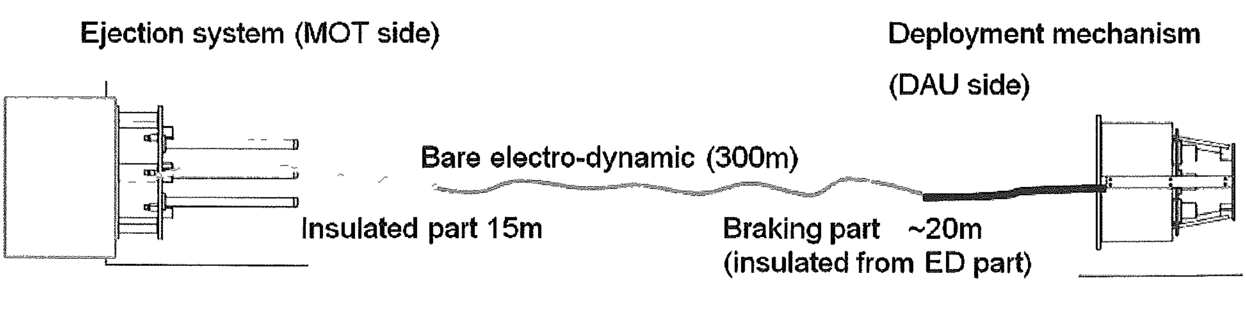

Fig. 3 T-REX Tape tether connection.

3. Sounding rocket experiment

3.1. Fast deployment of tape tether

The payload of the sounding rocket consists of a mother satellite (referred t0 as MOT: MOTher satellite) and a daughter satellite (referred to as DAU:DAUghter satellite) connected by bare electro-dynamic tether, tether deployment system, as shown in Fig. 3

Tether of length 300 m was planned to be deployed within 120 s (Figs.2, 3). Precise estimation of the residual thrust is not possible and the start of experiment is delayed in about 60 seconds (X+120) in order to alleviate the effect of the residual thrust, which is inherent for the solid motor rocket as S520.

The present mission requires a reliable and robust deployer because the bare tape tether is shown to have many unknown dynamic characteristics and a complex dynamic behavior. The deployment system employed a foldaway storage method. The present foldaway tape tether deployer was based on a new concept "Inverse ORIGAMI (Tape folding)" method as shown in Fig.4 and is totally different from the usual reel type tether deployers. This innovative storage method can afford reliable fast deployment and is a key idea of the proposal to satisfy the requirements of the science mission.

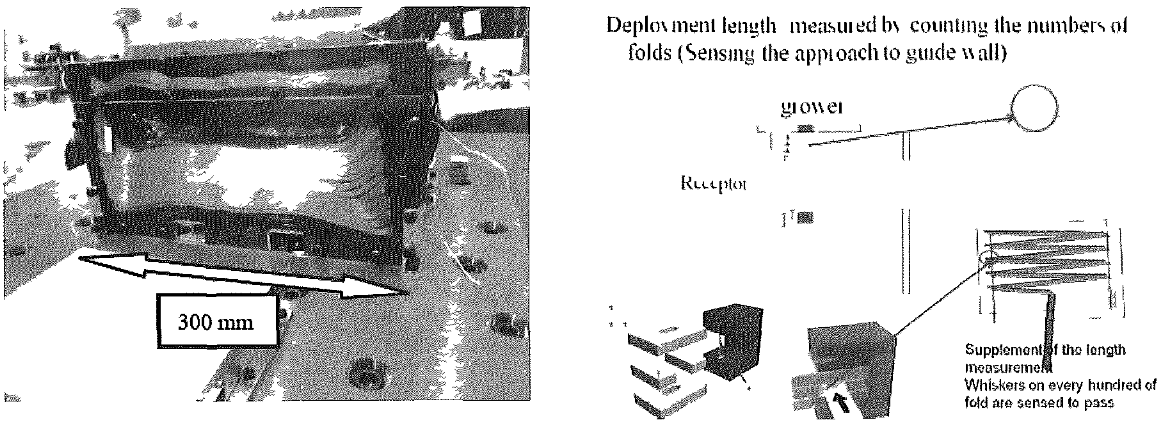

Fig.4 Tape tether folded in a box and tether length measurement.

Figure 4 shows the folded tape tether in a box and the device of counting the number of folds for tether length measurement. The length of tether deployment was measured by counting the number of folds passing through three receptors of emission from three LEDs. The count of the folding was decided by the majority of three sets of the counters and was permitted to count one for 0.6m if more than two sets of the counters agree. A supplemental device for the measurement of tether length was to sense and count the number of whiskers attached at every hundred of folds as shown in Fig.4 and also to sense different colors marked at every 25 m.

In order to remove any effect due to contaminations, the initial velocity of the deployment was given by the kinetic energy of loaded springs installed on the ejector with long stroke-guide shafts. The deployment sequence was designed under the constraints of the system including tape tether toughness and structural load constraints. Figure 5 is a schematic figure of the ejection system employed in the present project. The DAU was ejected through three springs from MOT. The three

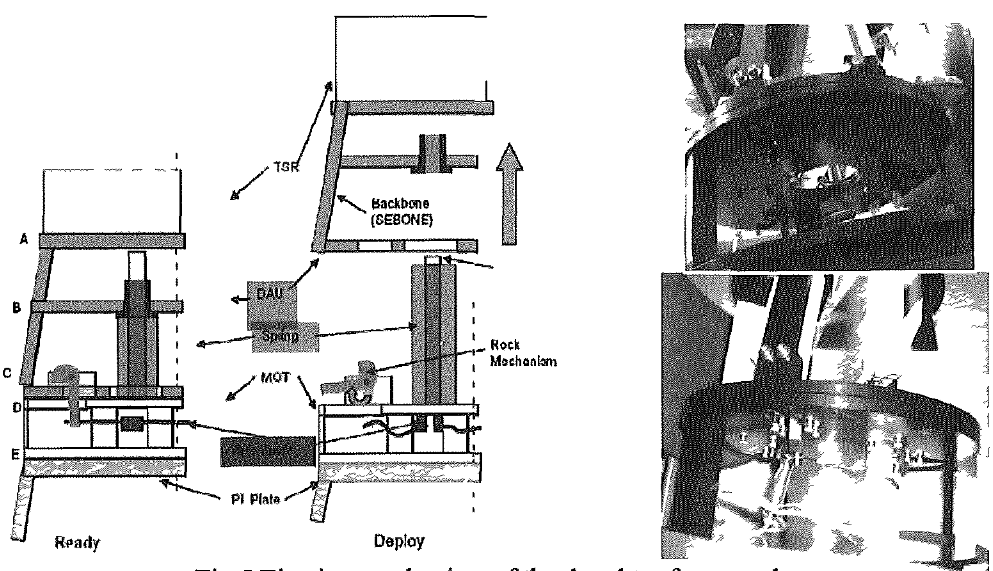

Fig.5 Ejection mechanism of the daughter from mother.

springs were fixed in a compressed state before the ejection and downside of DAU was sustained by three hooks constrained by a wire in tension. The wire was cut by a wire cutter at the predetermined time on the signal sent from the rocket. The tension of the wire was designed to sustain to the maximum of 100G along the DAU symmetric axis and managed throughout the process. The DAU was ejected in the velocity about 3m/s after the separation unwinding the tape tether from MOT.

More than eleven kinds of methods were employed for verification in the reliability of deployment for the present project. Deployment study of tether in high-confidence is classified to the following twelve schemes including the categories of 1) ejection and/or 2) extraction (winding) test. Both of the extraction and ejection tests, idea to cancel the effect of gravity on the ground test and hardware and/or software test may be cooperated.

Figure 6 shows the result of tether deployment in the space demonstration and its fitting curve. The folding number was counted for (220+1) times and it is shown that the tape tether was deployed to 132.6 m (0.6 m per count: error exists as less counting for a few of fold.). The data was also confirmed by the data obtained by the string sensors and the color sensor by every checker point at 25, 50, 75, 100, and 125 m (Fig.6).

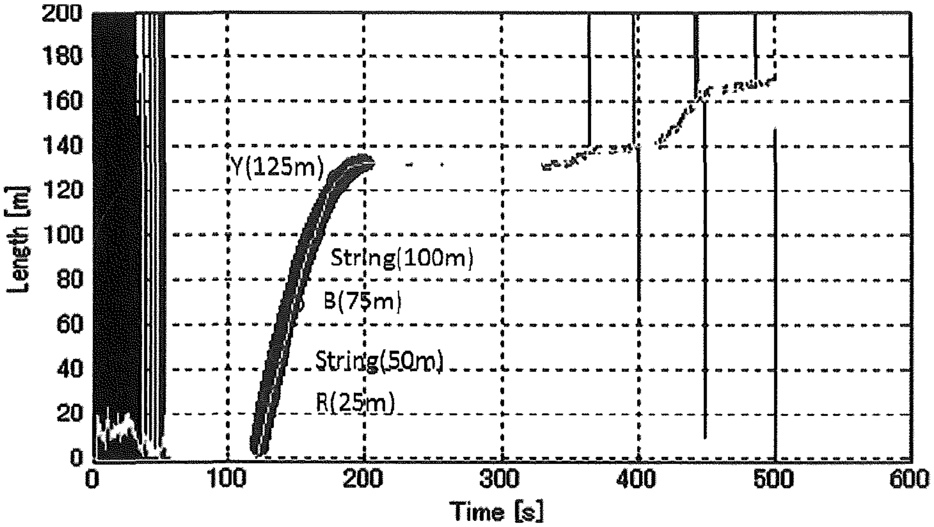

Fig.6 Length data in space demonstration: Deployed to 132.6m (Measured by the folding number counter 0.6m* (220+1))

The GPS system was equipped on both of the vehicles connected by tether and their relative position is measured. Figure 7 shows the GPS data and the successful deployment of tether is confirmed. It is also seen that the DAU moved back to the MOT after full deployment. The range between the MOT and DAU is seen to be about 125 m and is decreasing. Tether is supposed to slack after the full deployment as shown in Fig.7. After the separation at X+120 seconds, the range increased.

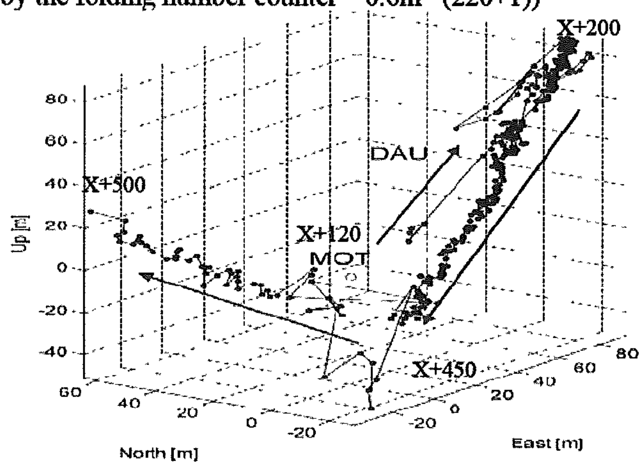

Fig.7 GPS data of the daughter(DAU) and mother (MOT) in space demonstration.

The length in the tape tether deployment could not reach to the total loading length of 300m. The drag in the deployment is supposed to be greater than the estimation in the on-ground experiments. Some reasons are supposed to cause the incomplete deployment including the deformation of tether, the centrifugal force due to the spin of the rocket and an excessive drag in the vacuum environment. This fact is now under analysis in a variety of experiments.

It should be noted however that the high fidelity is confirmed for the deployment scheme employing the tape tether folding and that the length of 132.6 m is the world record of the longest deployment in the space tape tether over the length of 22 m of ATEx (Advanced Tether Experiment) satellite [Ref.10].

One of the specific features of the present demonstration is the employment of many cameras as shown in Fig.8. Two still cameras and one TV camera in Ku band are mounted on the S520-25 sounding rocket, DAU, and MOT, respectively. The pictures are obtained in 1 Hz by the still cameras and in 30 Hz movie by the Ku camera. Figure 9 shows the photograph of the still camera (CAM #1) located on the DAU and was taken to the direction of the MOT after the ejection.

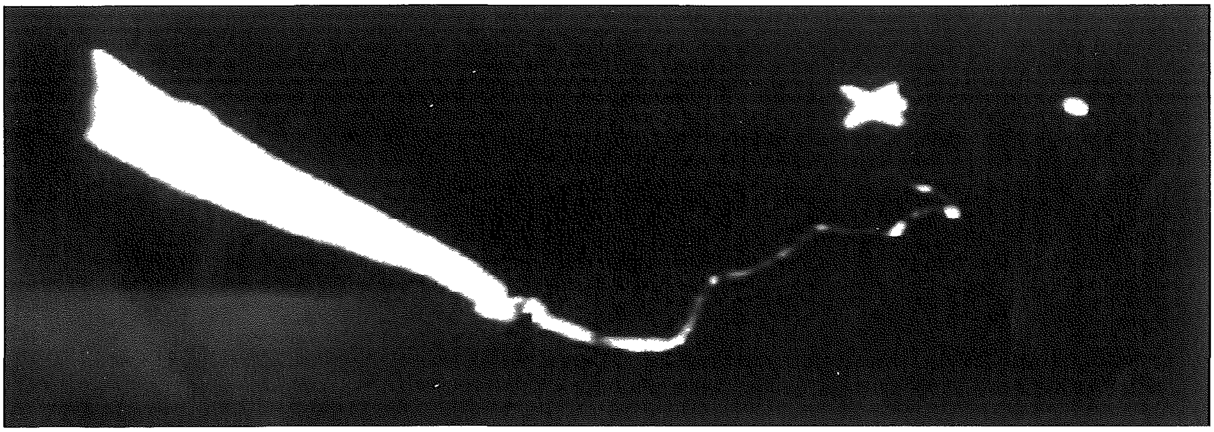

Fig.8 Tether observed by a camera on the daughter (Mother is seen as a star at the end of EDT).

3.2 Science Experiment

3.2.1 Verification of Current Collection Theory in Orbit [Ref.5]

In the first phase of the science experiment, broad testing conditions for vilification of OML collection were arranged: two cross section shapes, two sizes, collection within and beyond the OML regime, collection of electrons and of ions (with their different effects of geomagnetic field and relative plasma motion). A series of change in bias values, as the supply voltage setting, was not demonstrated due to discharge of electric battery before the start of the experiment. The data obtained, however, are under analysis of scientists of the T-Rex team and expected to verify the current collection theory in orbit.

3.2.2 EDT demonstration

In the first phase of the science experiment, the negative terminal of the power supply is switched to be connected to a hollow cathode, and the positive terminal to the tape tether. Electrons collected by the tape tether cross the supply and are ejected at the hollow cathode. Electron collection by a bare tape, which is involved in most electro-dynamic tether applications, would thus be directly tested in this phase, providing further consistency checks on the results. Total experiment time was 30 seconds starting X+240 s after the launch and finished after X+270 s when the hollow cathode shutdown. The present science experiment, the verification of EDT, is an operation as the rare experiment in the world. In the experiment, electrons were ejected from the ignited hollow cathode and collected by the bare electro-dynamic tether, which is negative biased by a battery device.

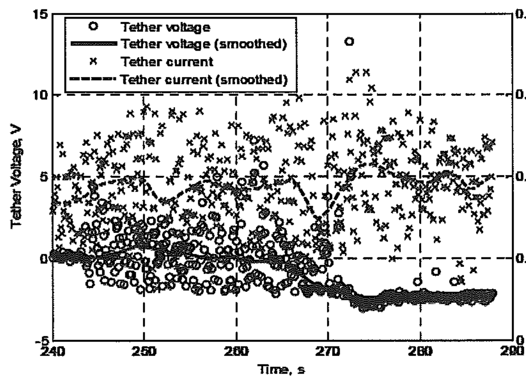

Fig.9 Tether voltage (blue) and current (red) during the second phase of science experiment.

The data are obtained as shown in Fig.10 for the charged particle collection by the induced electromotive force on EDT, and for the charged particle collection characteristic by the space potential probe.

4. Conclusion

Results of the space demonstration of science and engineering technologies of a bare electrodynamic tether (EDT) are reported in this paper. The international campaign between Japan, USA, Europe and Australia is the suborbital flight of the sounding rocket S520-25 and the method of "Inverse ORIGAMI (Tape tether folding)" is employed in order to deploy the bare EDT in a short period time of the suborbital flight. The method has shown high reliability in the deployment of tape tether and resulted in bare EDT tape tether with length 132.6 m as the world record of the length deployment of tape tether. This paper has described some features of the present bare EDT tape tether system including the ejection mechanism of the folded tape tether and the length measurement system. In the present T-Rex project, deployment length of loaded tape tether was not reached but the longest deployment record was obtained and fundamental experiments were performed about EDT.

The drivers for the electro-dynamic tether are underlies in the low cost, simple mission concept, and fast realization possibility. On the other hand, there are features such as the difficulty of handling and such complex behaviors as flexibility has been demonstrated. The present T-Rex project is one of the advancement of tether technology for the application including such a number of interesting and useful operations of space tether technology as the space elevator system with very long tape tether extending to 100,000 km.

References

1) Sanmartin, J.R., Martinez-Sanchez, M., and Ahedo, E., "Bare Wire Anodes for Electrodynamic Tethers", *Journal of Propulsion and Power*, Vol. 9, No. 3, 1993, pp. 353-360.
2) Kruijff, M., van der Heide, E.J., Vannaroni, G., Dobrowolny, M., and De Venuto, F., "Long Term Stability of Bare Conductive Tethers: Combined Results from Plasma Chamber Tests and Advanced Simulations" *Space Technology and Applications International Forum 2001*, Albuquerque, NM, February 2001.
3) Fujii, H. A., Watanabe, T., Sahara, H., Kojima, H., Takehara, S., Yamagiwa, Y., Sasaki, S., Abe, T., Tanaka, K., Oyama, K., Les Johnson, C., Khazanov, G. V., Sanmartin, J. R., Charro, M., Kruijff, M., van der Heide, E. J., Rubin, B., Garcia de Quiros, F. J., Trivailo, P. M., and Williams, P., "Space Demonstration of Bare Electrodynamic Tape-Tether Technology on the Sounding Rocket S520-25," *AIAA 2011-6503, AIAA Guidance, Navigation, and Control Conference*, 08 - 11 August 2011, Portland, Oregon.
4) Onishi, T., Martinez-Sanchez, M., Cooke, D.L., and Sanmartin, J.R., "PIC Computation of Electron Current Collection to a Moving Bare Tether in the Mesothermal Conditionat" *(Paper 01-245), 27th International Electric Propulsion Conference*, NASA, Pasadena, CA, 2001;
5) van Dijk, A., Kruijff, M., van der Heide, E.J., and Lebreton, J.P., "Self-Accelerating Tethers around Jupiter", *ESA, Final Report, Noordwijk*, November 2003.
6) Fujii, H.A., "New Space Technology: 1 km Tether to 100,000 km Space Elevator", *The VIP Scientific Forum of the International Conference on Advances in Internet Technologies and Applications 2004*, West Lafayette, IN, July 2004.
7) Cosmo, L.M., and Lorenzini, C.E.: Tethers in Space Handbook Third Edition, prepared for NASA MSFC by Smithsonian Astrophysical Observatory, Cambridge, MA, 1997.
8) Fujii, H.A., Watanabe, T., Kojima, H., Oyama,K., Kusagaya, T., Yamagiwa, Y., Ohtsu, H., Cho, M., Sasaki, S., Tanakaka, K., Williams, J., Binyamin, R., Les Johnson, C., Khazanov, G., Sanmartin, J.R., Lebreton, J-P., van der Heide, J.E., Kruijff, M., Pascal,F., and Trivailo, P. "Sounding Rocket Experiment of Bare Electrodynamic Tether System", *Acta Astronautica*, Vol.64, pp313-324(2009).
9) A. Van Dijk., M. Kruijff, E.J. van der Heide, J.P. Lebreton, Lebreton, "A Lightweight Bare Rotating Tether System for Jovian Atmospheric Entry", *IAC-03-S.P.05, 54th International Astronautical Congress of the International Astronautical Federation, 2003*, pp. 603–612.
10) http://code8100.nrl.navy.mil/programs/atex.htm